Searches for the Higgs Boson and Extra Dimensions at the LHC

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On behalf of the ATLAS and CMS collaborations

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The ATLAS and CMS collaborations, at the Large Hadron Collider at CERN, are finalizing the construction, installation and commissioning of their detectors and prepare the physics analyses. The search for the Higgs boson, a key component in the Standard Model description of electroweak symmetry breaking, is extensively studied. The LHC experiments are also dedicated to the search for new physics beyond the Standard Model, Extra Dimensions provide interesting scenarios in that context.

1.1 LHC, ATLAS and CMS in a few words

The LHC (Large Hadron Collider) is a proton-proton collider in construction at CERN. Protons will be accelerated to 7 TeV at the end of 2008, to provide an energy in the center-of-mass of 14 TeV in the collision. The low luminosity regime ($10^{33}\ cm^{-2}s^{-1}$) will allow to accumulate $\sim$30 fb^{-1} during the first three years. A high luminosity regime ($10^{34}\ cm^{-2}s^{-1}$) is expected in a second period to provide $\sim$300 fb^{-1} by 2014/2015. The large luminosity of LHC will imply additional proton-proton interactions per bunch crossing (every 25 ns) : $\sim$2 at low luminosity to 25 at high luminosity, whose presence will complicate the data analyses.

ATLAS (A Toroidal Lhc ApparatuS) and CMS (Compact Muon Solenoid) are two large general-purpose particle physics detectors installed at two collision points of the LHC. These two collaborations have made different choices for the subsystems designed to measure energy and momentum of photons, electrons, muons, jets and missing E_T [1] up to a few TeV, to be both at the end optimized for the search of the Higgs boson and new particles predicted in models beyond the Standard Model. More details on the status of the ATLAS and CMS detectors are given in Ref. [1].

1.2 The Standard Model and the Higgs boson

The Standard Model (SM) is "the" theory accepted by all the particle physicists to describe the electroweak and strong interactions. It is a quantum field theory with local gauge symmetries $SU(3)$x$SU(2)$x$U(1)$, in which the matter particles are grouped into 3 leptons families (e and ν_e, μ and ν_μ, and τ and ν_τ) and 3 quarks families (u and d, c and s, and b and t). The interactions between them are propagated by bosons: the photon for the electromagnetism, W^+, W^- and Z^0 for the weak interaction and 8 gluons for the strong force. Mass terms are not allowed by chiral structure for the fermions, and by gauge symmetry for the gauge bosons. The mass generation should therefore be introduced via a symmetry breaking.

A spontaneous symmetry breaking allows preserving the renormalizability in the electroweak sector, giving mass to the Z and W bosons and preserving a photon with zero mass. The mechanism of Brout, Englert and Higgs [2] proposes a doublet of scalar fields under $SU(2)$ with a scalar potential V(Φ) and a fundamental state of the field for $|\Phi| = v/\sqrt{2}$, with $v \sim 246$ GeV. Three degrees of freedom are used to provide mass to the $W^\pm$ and Z^0 bosons, and the last one forms one physical Higgs boson with mass M_H, such that $M_H^2 = 2\ \lambda v^2$, but with an unknown value of λ. The fermions get their mass through interaction with the scalar field (with arbitrary couplings).

In addition of being a beautiful solution to provide mass to particles, the Higgs boson is also useful to regulate the calculations at high energies, as for the unitarity of the $W_L W_L$ scattering. The only problem of this

[1] The missing E_T characterizes the presence of a particle which escapes the detector without leaving any signal, as in the case of a neutrino for example.

electroweak symmetry breaking mechanism is that the Higgs boson has not been discovered yet... The search for the Higgs boson represents therefore a key component of the physics program of high energy experiments currently in operation or starting soon.

The Standard Model of particle physics has been remarkably confirmed by experiment since 30 years, but unfortunately it does not answer all the actual questions : Why are there three families of quarks and leptons? Is there some pattern to their masses? Are the quarks and leptons really fundamental, or do they have a substructure? What is the dark matter made of? How to explain the matter-anti-matter composition of the universe? How to include gravity in the SM? ... So many questions which indicate a need to go beyond the SM.

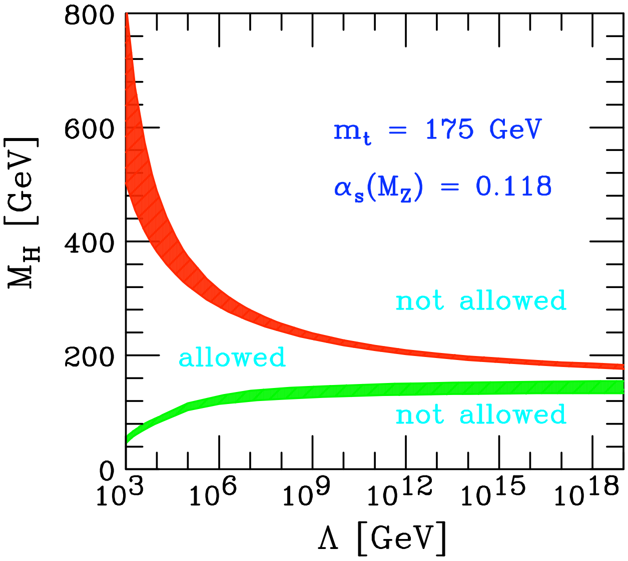
1.3 Existing limits on the Higgs mass

Even if the Higgs boson has not been discovered yet, a lot of constraints on its mass exist.

First, many theoretical arguments predict a Higgs mass below the TeV scale, as for example the unitarity of the WW scattering. The Triviality bound imposes an upper limit on the Higgs mass depending on the energy cut off Λ at which the SM becomes trivial (i.e. the self-coupling of the Higgs becomes infinite): for $\Lambda \sim 10^{16(3)}$ GeV, $M_H < 200$ (1000) GeV/c^2. A lower bound on the Higgs mass comes from the vacuum stability argument: fermionic contributions could lead to negative self-coupling for too small λ, where the vacuum is not a minimum anymore. To prevent this, an energy cut off Λ is introduced, leading to $M_H > 130$ (70) GeV/c^2 for $\Lambda \sim 10^{16(3)}$ GeV. These theoretical constraints on the Higgs boson are presented on Figure 1.1(left), as a function of Λ.

Secondly, on the experimental side, a lower limit on the Higgs mass has been set by direct searches at LEP-2 [4]: $M_H > 114$ GeV/c^2 at 95% confidence level (CL). From an adjustment of the electroweak data performed by the LEP Electroweak Working Group [5] [2] and shown on Figure 1.1(right), an upper limit of $M_H < 144$ GeV/c^2 at 95% of CL has been extracted, this value increases to 182 GeV/c^2 when including the direct search limit.

[2] This fit uses the latest measurement of M_{top}= 170.9 GeV/c^2.



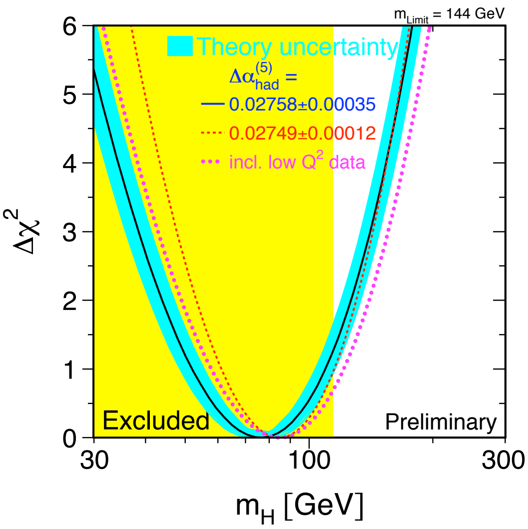


Figure 1.1. Left: Theoretical constraints on the Higgs boson. The red bound comes from triviality argument and the green one from vacuum stability. The allowed region is located between these two constraints [3]. Right: $\Delta\chi^2$ curve derived from high-Q^2 precision electroweak measurements, performed at LEP, SLD, CDF, and D0, as a function of the Higgs boson mass, assuming the SM to be the correct theory of nature [5].

1.4 Search for the Higgs boson at the LHC

The key points to define a strategy for detecting the Higgs at the LHC are of course the production rates and the decay branching ratios of the Higgs boson but also the background level per process.

The main production mechanism of the Higgs boson at the LHC, as shown on Figure 1.2(left) [6] as a function of the Higgs mass, is the gluon-gluon fusion mode ($gg \to H$), via a top quark loop. The second most important production mode is the Vector Boson Fusion (VBF, labelled Hqq on that figure), whose particular topology without color exchange between the quarks [3], compensates the low rate of the process. Associated productions of the Higgs with gauge boson or heavy quarks have even lower cross sections. Currently, the cross sections are known at the NLO (next-to-leading order) or NNLO, with an error around 5% for VBF and ttH processes, to 10-20% for the gg fusion and WH, ZH production modes.

[3] and so called tag-jets in the forward regions of the detector

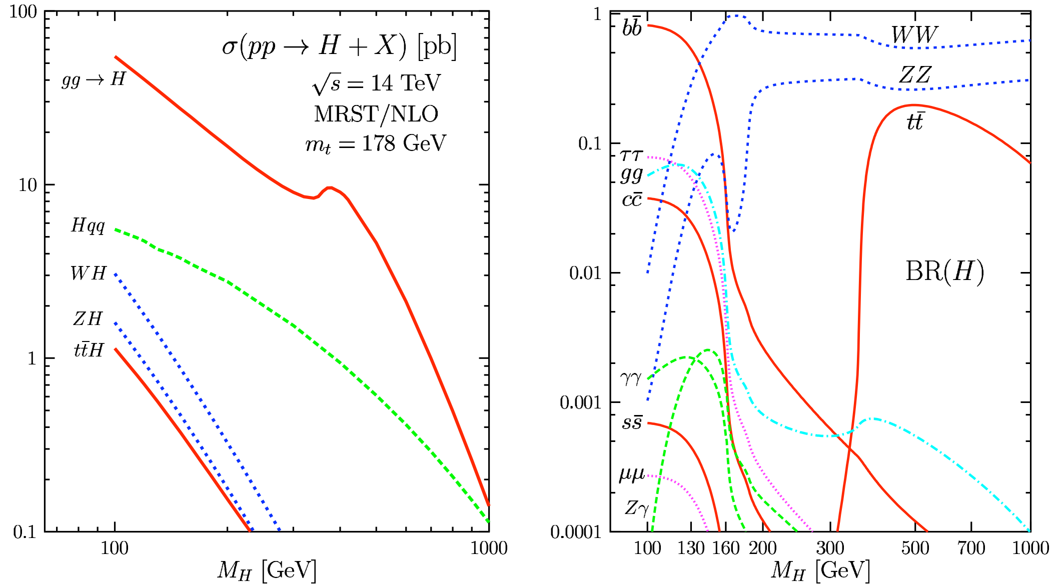


Figure 1.2. Left: Higgs production cross sections in the main channels at the LHC. Right: Branching ratios of the SM Higgs boson. Both graphs are presented as a function of the Higgs mass [6].

The different decay modes of the Higgs boson and their branching ratios (BR) are presented on Figure 1.2(right) [6]. At low mass value (for M_H <130 GeV/c^2), the Higgs decays dominantly into bb (with BR=75-50%) but this channel suffers from a huge QCD background. $H \to \tau\tau$ (BR=7-5%) can be studied in the VBF production mode, taking advantage of the distinct signature of the 2 forward jets. The BR for the Higgs decay into $\gamma\gamma$ through a loop of massive particle is only a few permil but combined with an excellent γ/jet separation, this channel is very interesting. $H \to VV$ $(V = Z, W)$ becomes the most important decay mode for M_H >130 GeV/c^2. Let's remark that $H \to ZZ^{(*)}$ decreases when 2 on-shell W bosons can be produced. And for $M_H \sim 400$ GeV/c^2, the decay in two top quarks starts to play a role. All BR are calculated at NLO, within few % error. For M_H below 200 GeV/c^2, the natural width of the Higgs boson is smaller than the experimental resolution; after that, it grows rapidly.

In the gg fusion dominant production mode, the $H \to \gamma\gamma$ is studied for $M_H < 140$ GeV/c^2. It relies on a precise reconstruction of the photons (energy resolution, angle with primary vertex information, conversion treatment) and a high rejection against jets (isolation cut, π^0 rejection).

Currently, both signal and background are computed at NLO. ATLAS and CMS have similar sensitivity on this channel. With optimized analyses (likelihood or neural network), they achieve both a significance of 8σ for a Higgs of 130 GeV/c^2 and an integrated luminosity of $30 fb^{-1}$.

At larger mass ($M_H > 130$ GeV/c^2), in the gg mode, $H \to ZZ^{(*)} \to 4l$ becomes an important channel to study. This very clean channel with 4 isolated leptons in the final state, leading to a narrow resonance over a small background, has a low statistics. The main experimental challenge is the lepton identification with high efficiency and resolution down to very low p_T ($\sim$ 5 GeV/c). Combining the leptons channels (4e, 2e2μ, 4μ) allows getting a significance of 5σ with an integrated luminosity of $20 fb^{-1}$ for $130 < M_H < 600$ GeV/c^2.

The $H \to WW^{(*)} \to 2l$ channel is very promising for masses around $2M_W$. The presence of neutrinos in the final state prevents the mass of the Higgs to be fully reconstructed. It is then particularly important for this analysis to achieve a very accurate background control and estimate. In addition to the gg mode, the $H \to WW$ channel is also studied in the VBF mode.

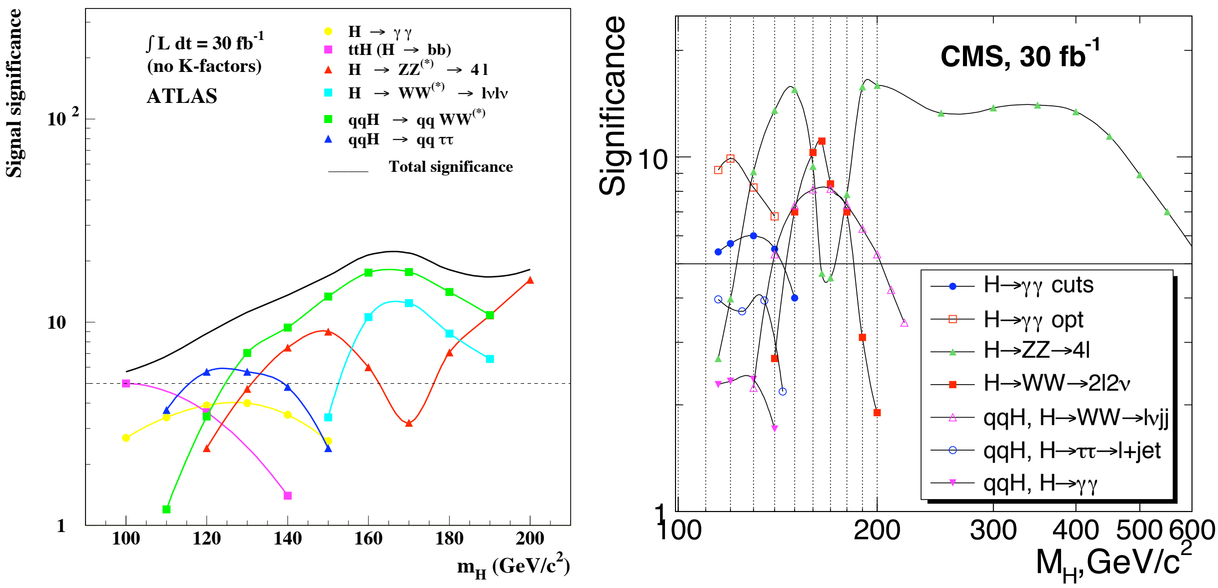


Figure 1.3. Signal significance expectation as a function of the Higgs mass for ATLAS [8] (left) and CMS [9] (right) with a integrated luminosity of 30 fb^{-1}, for different decay modes.

The results of ATLAS and CMS are summarized on Figure 1.3 [7, 8, 9]. Note that ATLAS uses LO in the plot, while CMS uses NLO cross sections. Apart from this, both experiments have similar sensitivity. New results are expected soon for ATLAS. The full mass range can already be covered after a few years at low luminosity. Several channels are available over a large range of masses. Vector boson fusion channels play an important role at low mass, complementing the $H \to \gamma\gamma$ analysis.

1.5 Introduction to Extra Dimensions

The actual theories that try to unify gravity with quantum mechanics and describe all physical phenomena are based on strings: 1-D objects with vibration modes that represent the elementary particles. One feature of string theories is the introduction of at least 6 new spatial dimensions to describe gravity, the strength of which becomes comparable to the other fundamental interactions at short distance. These new dimensions are assumed to be compactified with a size of the order of the Planck length (10^{-35}m) which is completely out of reach of any of the present experiments [10].

Recently, new concepts relative to Extra Dimensions (ED) have been explored within a string theory framework to address the so called Hierarchy problem, which manifests the large gap between the electroweak scale (10^3 GeV) at which the electroweak symmetry is broken and the Planck scale (10^{19} GeV) at which gravity effects become important. These new developments can lead to a decrease of the gravity scale in the TeV range, proposing a very rich phenomenology accessible to the LHC experiments.

In this picture, the space-time geometry is responsible for the apparent hierarchy. In the approach developed by Arkani-Hamed, Dimopoulos and Dvali (ADD) [11], the gravity field lines spread throughout the ED and gravity appears to be diluted. These spatial ED have to be of finite size, or compactified to avoid any deviation from Newton's law. The compactification radius R_C (or the compactification scale $M \sim 1/R_C$), as well as the number of ED are the free parameters of this class of scenarios.

Such models introduce a high dimensional space-time called the "bulk" populated by orbifolds (e.g. small intervals formed by the new dimensions) and a 4-D sub-dimensional space-time (called "brane") localized at the ends of these orbifolds. Particles propagating inside the bulk lead to the appearance on the 4-D brane of a tower of massive particles (the Kaluza-Klein (KK) excitations), which gave the same properties as the original particle but with a mass inversely proportional to the size of the ED.

In the ADD model, only gravitons are allowed to propagate in the bulk. The KK tower for graviton is a continuum of massive states, due to the large size of ED. In case of TeV^{-1} size ED [12], the gauge bosons could propagate outside our traditional 4-D world. The phenomenological consequence is that KK states of gauge bosons like the Z and the photon, with a mass around 1 TeV, could be produced at the LHC.

Another type of scenarios explains this apparent hierarchy by the strong curvature of space-time, as proposed by Randall and Sundrum (RS) [13]. The warped ED is compactified on an orbifold, holding two 4-D branes at fixed points. SM fields are localized on one side and the gravity is localized on the opposite side with a gravity scale of the order of 1 TeV. The hierarchy is then explained as an artefact of this warped ED in which gravity propagates. In this model, the graviton has a KK tower of well spaced states with mass of the order of a TeV for the first resonance.

ED are also a powerful tool for new model buildings to address other fundamental problems like the neutrino masses, the fermion mass hierarchy, gauge coupling unification, etc. A large number of possible scenarios have been proposed. This rich phenomenology leads particle physicists to define new strategies for the discovery and discrimination of the different scenarios.

1.6 Search for Extra Dimensions at the LHC

A first interesting signature to be searched for at the LHC is a large imbalance in the energy measured in the detectors in the projection transverse to the beam, detected in association with jets or leptons. Its origin can be explained by the emission of real KK excitations of graviton, which escape detection due to their small coupling to matter as in the ADD model [11]. Figure 1.4(left) shows the transverse missing energy spectrum for a direct production of gravitons in association with a mono-jet in the ADD model. LHC experiments will be able to probe the compactification scale up to 9

TeV (resp. 6 TeV) for 2 (resp. 4) ED with an integrated luminosity of 100 fb^{-1} [14].

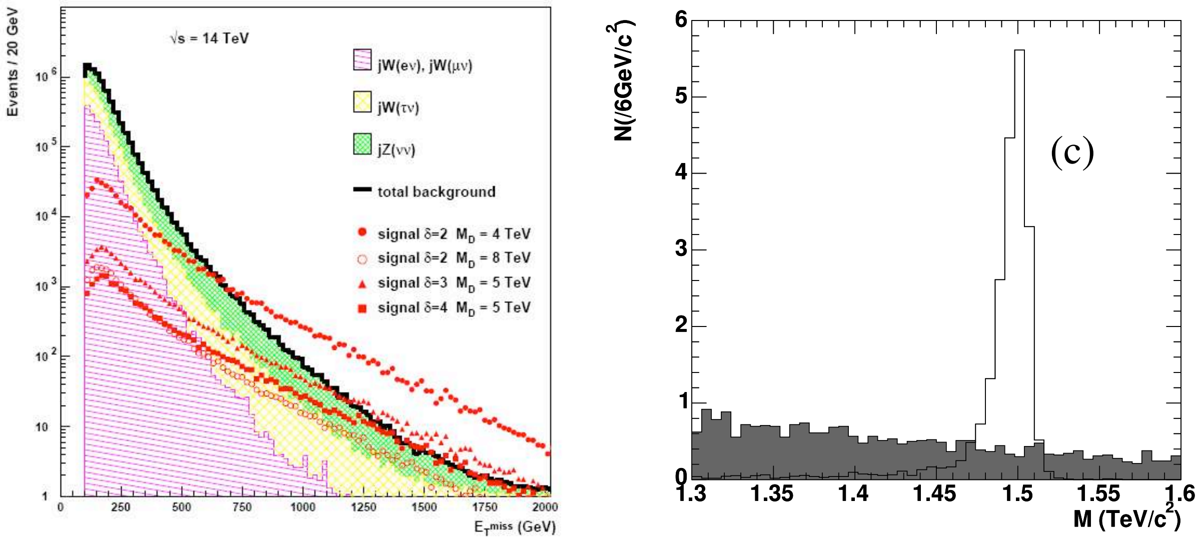


Figure 1.4. Left: Missing E_T spectrum in the ADD model [14]. Right: Invariant mass of the di-electron system in the RS model [15].

Deviations from the SM in the di-fermion spectra provide a second class of signatures. If the energy in the center of mass is sufficient, KK excitations of the graviton from the RS model, or of gauge bosons in TeV^{-1} models, could be produced and detected as peaks in the di-fermion mass spectrum. The KK excitations of gauge bosons would also interfere with SM gauge boson production, leading to deviations. Figure 1.4(right) shows a typical resonance in a di-electron spectrum for a first KK graviton excitation in the RS model with a mass of 1.5 TeV$/c^2$ and a coupling parameter to SM particles $c = 0.01$, above the SM background for an integrated luminosity of 30 fb^{-1} [15]. With less than $60 fb^{-1}$ the full region of interest of the RS model will be covered by the LHC [9].

After a resonance discovery, the identification question arises. To distinguish KK gravitons from KK Z/γ bosons or new Z' bosons, different approaches can be used simultaneously: use information from other decays or other new resonances, analyze the angular distribution of the decay products and the forward-backward asymmetry. But take note that such studies will take time.

1.7 Conclusions

The Higgs search constitutes a very active domain in the ATLAS and CMS collaborations. Early discoveries (with $<\sim 10 fb^{-1}$) could be possible for $H \to VV$ at large mass. The low mass region is more challenging, optimized Higgs analyses predict a discovery after 3 years.

Various scenarios of Extra Dimensions have been studied by both collaborations and provide interesting discovery potential for the LHC. Whereas new physics could potentially appear quickly at the LHC, its identification will take more time.

For all analyses, a good understanding of the detector is needed to assess performance and understand background shapes. At less than one year to the first collisions, it is now time to focus to get ready for data.

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